ILLUMINATION SYSTEM WITH A PLURALITY OF LIGHT SOURCES

The invention concerns an illumination system for wavelengths ≤ 193 nm, i.e.,
VUV and EUV-lithography with a plurality of light sources, for example, as well

5   as a mirror or lens device for producing secondary light sources, comprising
several mirrors or lenses, divided into raster elements.

In order to allow even further reduction in the structural width of electronic
components, especially to the submicron range, it is necessary to reduce the

10   wavelength of the light used in microlithography.

For wavelengths smaller than 193 nm, lithography with weak x-rays or so-called
EUV-lithography is discussed.

15   A suitable illumination system for EUV-lithography should homogeneously or
uniformly illuminate, with as few reflections as possible, a pregiven field for EUV-
lithography, especially the annular field of an objective lens, under lithography
requirements. Furthermore the pupil of the objective lens should be illuminated
up to a particular degree of filling σ, independently of the field, and the exit pupil

20   of the illumination system should be situated in the entrance pupil of the
objective lens.

Regarding the basic layout of EUV-illumination systems, we refer to the
applicant's pending applications EP 99 106348.8, submitted on March 2,1999,

25   entitled "Illumination system, especially for EUV-lithography", US Serial No.
✓ 09/305,017, submitted on May 4, 1999 entitled "Illumination system particularly
for EUV-lithography", and PCT/EP 99/02999, submitted on May 4, 1999, entitled
"Illumination system, especially for EUV-lithography", whose disclosure contents
are incorporated in their entirety in the present application.

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The following are discussed herein as light sources for EUV-illumination systems:

laser plasma sources

5   pinch plasma sources

synchrotron radiation sources

In the case of laser plasma sources, an intensive laser beam is focused onto a target (solid, gas jet, droplet). The target is heated so strongly by the excitation

10   that a plasma is formed. This emits EUV-radiation.

Typical laser plasma sources have a spherical beam, i.e., a radiation angle of 4 π, as well as a diameter of 50 µm to 200 µm.

15   In pinch plasma sources, the plasma is produced by means of electrical excitation.

Pinch plasma sources can be described as volume radiators (D = 1.00 mm), which emit in 4 π, whereby the beam characteristic is dictated by the source

20   geometry.

In the case of synchrotron radiation sources, one can distinguish three types of sources at present:

25   -   bending magnets

-    wigglers

-    undulators

In bending magnet sources, the electrons are deflected by a bending magnet

30   and emit photon radiation.

Wiggler sources comprise a so-called wiggler for deflection of the electron or an electron beam, and this wiggler comprises a multiple number of alternating polarized pairs of magnets arranged in rows. If an electron passes through a

5   wiggler, it is subjected to a periodic, vertical magnetic field and the electron oscillates in the horizontal plane. Wigglers are also characterized by the fact that no coherency effects occur. The synchrotron radiation produced by a wiggler is similar to a bending magnet and radiates in a horizontal solid angle. In contrast to the bending magnet, it has a flux that is intensified by the number of

10   poles of the wiggler.

There is no clear dividing line between wiggler sources and undulator sources.

In case of undulator sources, the electrons in the undulator are subjected to a

15   magnetic field of shorter period and smaller magnetic field of the deflection poles than in the case of a wiggler, so that interference effects occur in the synchrotron radiation. The synchrotron radiation has a discontinuous spectrum based on the interference effects and emits both horizontally as well as vertically in a small solid-angle element; i.e., the radiation is highly directional.

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It is critical for an EUV-illumination system to provide a sufficiently high Lagrange optical invariant or *etendu*. The Lagrange optical invariant of a system is defined as the product of the illuminated surface times the square of the aperture.

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If the aperture in the plane of the wafer is in the range NA_{wafer} = 0.1-0.25, then in the case of 4:1 systems an aperture in the reticle plane of $NA_{reticle}$ = 0.025-0.0625 is needed. If the illumination system is supposed to illuminate this aperture homogeneously and independent from the field up to a filling degree of σ = 0.6,

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for example, the EUV-source must have the following 2-dim Lagrange optical invariant or *etendu*: (LC).

$$LC_{ill.} = \sigma^2 \, LC_{Obj} = 0.149 \text{ mm}_2 - 0.928 \text{ mm}^2$$

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The Lagrange optical invariant LC, is generally defined as follows for the lithography system described herein:

$$LC_{ill.} = \sigma^2 x \cdot y \cdot NA^2 = \sigma^2 A \cdot NA^2,$$ wherein A is the illuminated area. The area

10 comprises 110 mm x 6 mm, for example, in the reticle plane.

The Etendu of a laser plasma source can be roughly calculated as the product of the illuminated surface of an imaginary unit sphere around the source and the

15 square of the aperture angle at which each field point of the imaginary unit source sees the spherical source.

$$LC = A \cdot NA^2$$
$$A^{LPQ} = 2\pi[\cos(\theta_1) - \cos(\theta_2)]$$
20 $$NA \approx r_{source}/1 \text{ mm} = 0.100$$

where θ_1 is the minimum beam angle with respect to the optical axis and θ_2 is the maximum beam angle with respect to the optical axis

25 $$LC_{LPQ} = 2\pi[\cos(\theta_1) - \cos(\theta_2)] \cdot r^2_{LPQ}$$

With the typical source parameters:

1. $r_{LPQ} = 0.1$ mm, $\theta_1 = 0°$, $\theta_2 = 90°$ yields: $LC_{LPQ} = 0.063$ mm^2. This corresponds to 27% of the required value of the Lagrange optical invariant LC_{ill} of, for example, 0.236 mm^2.

5   2. $r_{LPQ} = 0.025$ mm, $\theta_1 = 0°$, $\theta_2 = 90°$ yields: $LC_{LPQ} = 0.0039$ mm^2. This corresponds to 1.7% of the required value of the Lagrange optical invariant of, for example, $LC_{ill} = 0.236$ mm^2.

The Lagrange optical invariant LC_{Pinch} of a pinch plasma source with a diameter

10   of 1 mm, $\Omega = 0.3$ sr, for example, is:

$$LC_{Pinch} = A \cdot NA^2 = \pi \cdot 1 \text{ mm}^2 / 4 \cdot 0.3053^2 = 0.073 \text{ mm}^2.$$

Thus, the pinch plasma source provides 31% of the required value of the

15   Lagrange optical invariant of, for example, $LC_{ill} = 0.236$ mm^2.

The Lagrange optical invariant or *Etendu* for the undulator source can be estimated by a simplified model assuming a homogeneous two-dimensional radiator with diameter

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$\varnothing = 1.0$ mm and aperture $NA_{Und} = 0.001$ with

$LC_{Und} = A \cdot NA^2$

$A_{Und} = \pi \cdot (\varnothing / 2)^2$

$\qquad = 0.785$ mm^2

25   $NA_{Und} = 0.001$

as

$LC_{Und} = A \cdot NA^2 = 0.00000079$ mm$^2 = 7.9\text{e-}07$ mm^2.

As can be seen from this rough calculation the Etendu or Lagrange optical invariant of the undulator source is much too small in comparison to the required value of the Lagrange optical invariant.

5   To increase the Lagrange optical invariant, an illumination system comprising a synchrotron radiation source known from US 5,512,759, comprises a condenser system with a plurality of collecting mirrors, which collect the radiation emitted by the synchrotron radiation source and form it to an annular light beam that corresponds to the annular field being illuminated. By this, the annular field is

10   illuminated very uniformly. The synchrotron radiation source has a beam divergence > 100 mrad in the plane of radiation.

US 5,439,781 shows an illumination system with a synchrotron radiation source, in which the Lagrange optical invariant, is adjusted by means of a scattering

15   plate in the entrance pupil of the objective lens, wherein the scattering plate can comprise a plurality of pyramidal structures. Also, in US 5,439,781, the synchrotron radiation source has a beam divergence > 100 mrad. The synchrotron radiation according to US 5,439,781 is also focused, for example, by means of a collector mirror.

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The disclosure contents of both of the above-mentioned documents

        US 5,512,759
        US 5,439,781

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are incorporated into the disclosure contents of the present application by reference.

The object of the invention is to supply an illumination system of easy

30   construction having the required Etendu in the object - or reticle - plane.

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The object of the invention is solved in that several light sources are coupled in order to illuminate the exit pupil of the illumination system up to a predetermined degree of filling.

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The coupling of several light sources also results in an increase of intensity. A coupling of several light sources is possible as long as the total Lagrange optical invariant of all coupled sources is less than the Lagrange optical invariant of the illumination system LC_{ill}.

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There are three basic possibilities for coupling:

1. Addition method: Identical or similar illumination systems are distributed about an axis of the system. The exit pupil of the illumination system is
15   illuminated by the circular pupils of the system parts, which must not overlap. The partial pupils are located on the side face of a pyramid-shaped input mirror, which superimposes the light bundles on the object or reticle.

2. Mixing method: In this case, each system part illuminates the entire exit
20   pupil of the illumination system, but with regions free of light between the secondary light sources. The individual grids of the secondary light sources are staggered by superimposing, so as to uniformly fill the pupil. The coupling mirror consists of a raster element plate, whose raster elements or facets have the shape of pyramids. Each side face of an individual raster
25   element pyramid is illuminated by a secondary light source.

3. Segment method: Similar to the addition method. Unlike the addition method, a segment of any desired shape is illuminated by appropriate beam deflection, instead of a circular segment of the exit pupil.

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Preferred embodiments of the invention making use of at least one of the above-mentioned methods are the subject of the subsidiary claims.

The invention shall now be described by means of the drawings.

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Here:

Figure 1   shows a first embodiment of the invention, in which the light of several light sources is superimposed according to the addition

10   method.

Figure 2   shows the arrangement of the raster element field plates on an equilateral pyramid.

15   Figure 3   shows the illumination of the exit pupil of a system according to Figure 1.
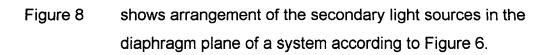
A   *Figures 4A-4D Show*

A   ~~Figure 4~~ ~~shows~~ illumination of the exit pupil with coupling of 3, 4, 5 and 6 sources.

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Figure 5   shows a second embodiment of the invention, in which the light of several light sources is coupled by the addition method in the diaphragm plane.

25   Figure 6   shows a third embodiment of the invention, in which the light of several light sources is coupled by the mixing method in the diaphragm plane.

Figure 7   shows arrangement of the field raster elements on the field raster

30   element plates of a system according to Figure 6.

Figure 8   shows arrangement of the secondary light sources in the
            diaphragm plane of a system according to Figure 6.

5   Figure 9   shows segment of the pupil raster element plate of a system
                 according to Figure 6 with a plurality of pyramids, on whose flanks
                 the pupil raster elements are located.

Figure 10   shows a fourth embodiment of the invention, in which light from
10   several light sources is coupled in the diaphragm plane by means
                of imaging raster elements according to the mixing method.

Figure 11   shows illumination of a segment of the pupil raster element plate in
            a system that operates according to the segment method.

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Figure 12   shows the illumination system of the second embodiment wherein a
            field lens is situated in a light path between the plurality of
            secondary light sources and the reticle plane and some rays are
            drawn from the two light sources to the exit pupil.

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Figure 13   shows a projection exposure system with the illumination system of
            Fig. 12.

Figure 1 shows the layout of a system in which the light sources are coupled
25   together according to the addition method. The light sources 1.1, 1.2 in the
     present case have a small source diameter, in this case laser plasma sources
     are further investigated.

Regarding the basic layout of EUV-illumination systems, we refer to the
30   applicant's pending applications EP 99 1 06348.8, submitted on March 2, 1999,

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entitled "Illumination system, especially for EUV-lithography", US Serial No. 09/305,017, submitted on May 4, 1999, entitled "Illumination system particularly for EUV-lithography", and PCT/EP 99/02999, submitted on May 4, 1999, entitled "Illumination system, especially for EUV-lithography", whose disclosure contents

5   are incorporated in their entirety in the present application.

Each system part 10.1, 10.2 is essentially identical in construction and comprises a light source 1.1, 1.2, a collector mirror 2.1, 2.2, and a field raster element plate 4.1, 4.2.

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The light of each source is collected by means of the collector mirror assigned to a particular source and transformed into a parallel or convergent light bundle. The field raster elements of the particular field raster element plate 4.1, 4.2 decompose the light bundle and create secondary light sources 6 in the

15   diaphragm plane of the illumination system. These secondary light sources are imaged by the field lens (not shown) or field mirror in the exit pupil of the illumination system, which is the entrance pupil of the objective lens (not shown). The field raster elements of the field raster element plate are arranged on the plate and oriented so that the images of the field raster elements are

20   superimposed in the reticle plane 9.

The systems are brought together where the field raster element plates are located. The field raster element plates are located on a pyramid, the number of the sides of the pyramid corresponds to the number of coupled partial systems.

25   The angle of inclination of the pyramid sides is chosen such that the illuminated fields of the partial systems in the reticle plane 9 are superimposed.

The partial systems parts 10.1, 10.2 are arranged such that their partial pupils fill the diaphragm plane of the illumination system optimally.

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In the embodiment shown in the drawings, the partial systems are oriented such that they possess a common system axis. The angular spacing of the partial system is then 360°/number of systems.

5   For four partial systems, Figure 2 shows the illumination of the pyramid, on each of the four lateral surfaces 20.1, 20.2. 20.3, 20.4 of the pyramid one field raster element plate of a partial system in the area of the illuminated surface 22.1, 22.2, 22.3, 22.4 is arranged.

10   The field raster elements are arranged and oriented such that the images of the field raster elements overlap in the reticle plane 9. The angle of inclination of the pyramid surfaces 20.1, 20.2. 20.3, 20.4 is chosen such that the illuminated fields of the partial system superimpose in the reticle plane.

15   The illumination in the diaphragm plane is provided by four circular partial pupils 30.1, 30.2. 30.3, 30.4, as shown in Figure 3, which in turn are divided into individual secondary light sources 6, corresponding to the number of illuminated field raster elements of the field raster element plates.

20   In Figure 3, the aperture of the total system is $NA_{Obj} = 0.025$ and the aperture of the system parts is $NA_{Teilsystem} = 0.0104$.

Depending on the number of coupled partial systems, one can imagine the arrangement and symmetries of the partial pupils 30.1, 30.2. 30.3, 30.4, 30.5, 25   30.6 as shown in Figure 5.

The maximum diaphragm diameters of the partial systems are derived from the total aperture NA_{Obj} of the objective lens in the diaphragm plane and the number of partial systems or subsystems.

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T,0130

$$NA_{Teilsystem} = \frac{NA_{Obj}}{1 + \dfrac{1}{\sin\left(\dfrac{\pi}{Anzahl}\right)}}$$

Whereby:

Teilsystem = partial system; Anzahl = number of partial systems

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When the pupil of each subsystem is filled, the pupil can be illuminated to η% of the maximum.

T,0131

$$\eta = Anzahl \cdot \frac{1}{\left(1 + \dfrac{1}{\sin\left(\dfrac{\pi}{Anzahl}\right)}\right)^2}$$

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Whereby:

Anzahl = number of partial systems

15 The following table gives $NA_{system\ part}$ and the filling factor η for $NA_{Obj} = 0.025$:

T,0132

Number of system parts	$NA_{system\ parts}$	Filling factor η_{max}
2	0.0125	0.500
3	0.0116	0.646
4	0.0104	0.686
5	0.0093	0.685
6	0.0083	0.667
7	0.0076	0.641

8	0.0069	0.613
9	0.0064	0.585
10	0.0059	0.557

Hence, the maximum attainable filling factor with the addition method using four

subsystems and NA_{Obj} = 0.025 is achieved with $\eta_{max} \approx 0.69$. As a boundary

5   condition, the overall Etendu of the coupled sources may not exceed the system

Etendu LC_{ill} = $\eta_{max} \cdot LC_{Obj}$; thus, we must always have:

$$\sum_{all\ sources} LC_i \leq LC_{ill}$$

10   *all sources*

Figure 5 shows a second form of embodiment of the invention, in which the light

sources 50.1, 50.2 are pinch plasma sources, for example. The source diameter

15   of the pinch plasma sources is not negligible.

A partial illumination system with pinch plasma source comprises the light

source 50.1, 50.2, a collector mirror 52.1, 52.2, which collects the light and

illuminates the field raster element plate 54.1, 54.2. The field raster elements of

20   the plate produce secondary light sources. At the location of the secondary light

sources, the pupil raster elements are arranged on a pupil raster element plate.

The field raster elements of the field raster element plate are used to shape the

field and the pupil raster element of the pupil raster element plate correctly

image the field raster element in the reticle plane. Preferably, each field raster

25   element is assigned to a pupil raster element. The light is guided by reflection

from the field raster elements of the field raster element plates to the pupil raster

element of the pupil raster element plate 56.1, 56.2 and from there to the reticle, or object 58.

The systems are brought together at the location of the pupil raster element

5   plates. The pupil raster element plates are located on a pyramid. The number of sides of the pyramid corresponds to the number of coupled subsystems. The angle of inclination of the pyramid sides is chosen such that the illuminated fields of the partial systems or subsystems are brought together in the reticle plane.

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If the subsystems have a common system axis, then the angular spacing of the system parts is 360°/number of systems and the pupil raster element plates of the subsystem are preferably arranged on the lateral surfaces of a pyramid, as shown in Figure 2.

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The advantage of the addition method of coupling is that identical or similar illumination systems can be coupled together. The raster element plates of the subsystems are separate and can thus be fabricated separately.

20   In the addition method, it should be noted that intensity differences of the individual sources are directly passed on to the illumination of the pupils, and thus the intensity of the partial pupils is dictated by the source power.

The intensity distribution in the diaphragm plane becomes independent of the

25   intensities of the individual sources if one mixes the secondary light sources in the pupil plane. This technique is also hereafter designated as the mixing method.

Whereas in the addition method the beam bundles of each source only

30   penetrate after passing through the diaphragm plane, in the mixing method the

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beam bundles penetrate in front of the diaphragm plane and are mixed in the diaphragm plane. The maximum aperture for each subsystem is adapted to the desired angle of filling of the objective aperture. As in the addition method, systems of identical construction can be coupled together for the individual

5   sources. They are uniformly arranged about a common system axis. The systems are coupled together in the plane of the secondary light sources.

Figure 6 shows an illumination system based on the mixing method for coupling of several light sources.

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The light sources once again are laser plasma sources. The same components as in Figure 5 are designated with the same reference numbers. In contrast to Figure 5, for example, there is a single pupil raster element plate 100, which includes a plurality of pyramids. The pupil raster element plate 100 is arranged

15   at the location of the secondary light sources, which are produced by the field raster elements. A secondary light source is located on each flank, or lateral side, of the plurality of pyramids.

The schematic representation of Figure 7 shows a typical arrangement of the

20   field raster elements 110 on the field raster element plate. Each field raster element plate produces a grid of secondary light sources in the diaphragm plane. The distribution of the secondary light sources in the diaphragm plane corresponds to the arrangement of the field raster elements.

25   By shifting the subsystems, as depicted in Figure 8, the grids of secondary light sources can be brought to be located next to each other, corresponding to the number of subsystems.

If four sources are coupled together, the arrangement of secondary light sources

30   6 shown in the schematic representation of Figure 8 is obtained. For the correct

superimposing of the four subsystems, each set of secondary light sources is located on a mirrored pyramid. The flanks of the pyramid are inclined such that the images of the field raster elements are superimposed in the reticle plane. The schematic representation of Figure 9 shows a segment of the pupil raster

5   element plate. One clearly recognizes the individual pupil raster elements 104 that are formed by the flanks of an equilateral pyramid 106.

If the Etendu (LC) of the individual sources is small, the pupil raster elements can be designed as plane mirrors, i.e., the flanks of the equilateral pyramids 106

10   are planar.

When the source diameter is not negligible, such as with pinch plasma sources, the pupil raster elements 104 must image the field raster elements in the object plane, for example, the reticle plane. In this case, a concave mirror surface 108 *, as shown in Figure 10,*

15   must be worked into the pyramid flanks.

The schematic representation of Figure 10 shows a system in which several pinch plasma sources are coupled with a pupil raster element plate comprising pupil raster elements with concave surfaces. The same components as in Figure

20   6 are given the same reference numbers.

The examples shown in Figures 5 through 10 are designed for four coupled sources. However, the same method can be used for three, five, six or more sources. The grids should then be shifted such that the secondary light sources

25   are located on the side faces of pyramids. The degree of filling of the pupil is limited similar to the addition method.

The advantages of the mixing method are that the individual sources are mixed in the pupil plane. Fluctuations in source intensity are not shown in the pupil as

inhomogeneous pupil illumination. Furthermore, the system pupil can be filled more uniformly with secondary light sources.

As a third method of coupling several light sources together, the segment
5   method shall be described.

The segment method works similar to the addition method. The coupled illumination systems are uniformly distributed about a common system axis. Each system has a corresponding segment to fill the diaphragm plane. Instead
10   of filling this segment with a circle as in the addition method, one can uniformly fill up the segment by orienting the field raster elements on the field raster element plate. Figure 11 shows the illumination of one of four segments 200 of the system pupil 202, when four sources are coupled together. In segment 200 secondary light sources 6 corresponding to the number of illuminated field raster
15   elements are formed.

In order for the individual light bundles to be correctly superimposed in the reticle plane, pupil raster elements must be arranged at the location of the secondary light sources, which deflect the light bundles so that the images of the
20   field raster elements are superimposed in the reticle plane. Depending on the size of the source, the pupil raster elements have planar surfaces for point like sources or concave surfaces for extended sources. Accordingly, field and pupil raster elements are tilted individually and without symmetry.

25   The advantage of the segment method is the optimal filling of the diaphragm plane with secondary light sources 6 by a pairwise tilting of field and pupil raster elements.

Although no optical components have been depicted in the preceding examples
30   of embodiments of the illumination systems after the lenses or mirrors with raster

elements, it is obvious to the person skilled in the art that field lenses or field mirrors must be provided after the lenses or mirrors with raster elements in order to shape the annular field in the reticle plane and to image the diaphragm plane into the exit pupil of the illumination system, for example. This is shown in Figure

5   12. The illumination system of the second embodiment, shown in Figure 5 was adapted by introducing a field lens 300 between the pupil raster element plates 56.1 and 56.2. The field lens 300 represents an optical unit, which can also comprise two or more mirrors. The field lens 300 images the plurality of secondary light sources formed on the pupil raster element plates 56.1 and 56.2

10 into the exit pupil 310. In this regard, concerning the basic layout of EUV illumination systems, refer to the applicant's pending applications EP 99 1 06348.8, submitted on March 2,1999, entitled "Illumination system, especially for EUV-lithography", US Serial No. 09/305,017, submitted on May 4, 1999 entitled "Illumination system particularly for EUV-lithography", and PCT/EP 99/02999,

15 submitted on May 4, 1999, entitled "Illumination system, especially for EUV-lithography", whose disclosure contents are incorporated in their entirety in the present application.

An EUV-projection exposure system is shown in Figure 13. The illumination

20 system is already shown in Figure 12. The reticle 58 is imaged by the projection objective lens 320 onto the wafer 330. The EUV-projection exposure system can be realized as a stepper or scanning system.